

Original Article

Percentile curves and reference values for 2000-m rowing ergometer performance time in international rowers aged 14-70 years

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ABSTRACT

The aim of this study was to provide percentile curves and reference values for the performance in 2000-m maximal effort on rowing ergometer. A cross-sectional study was carried out with a non-probabilistic sample (n=15420) obtained from an on-line ranking of indoor rowing and made from results between 2010 and 2014 recorded in 2000-m official races. Percentile curves and reference values were calculated using Generalized Additive Models for Location, Scale and Shape (GAMLSS) with a transformation of data to Box-Cox Power Exponential distribution and cubic splines as smoothing technique with age as the explanatory variable. This study is the first to present percentile curves and reference data to evaluate 2000-m performance time (indirect measure of mechanical power) in rowing ergometer depending on age (14-70) for both sexes and body-mass classifications (light- and heavyweight rowers). These curves and values are of interest in assessing indoor rowing performance and in measuring the specific physical condition of rowers in 2000-m regattas on-water. Percentiles also can be useful to predict performance levels in oncoming ages. **Keywords:** Aging human; Exercise performance; Fitness assessment; Rowing performance; Talent development.

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INTRODUCTION

Rowing is a sport discipline in which an individual or crew drive a boat-rower system on-water as effect of propulsion forces generated by the repetition of a stroke cycle (Kleshnev, 2010; Soper & Hume, 2004). It is not only considered a competitive sport, but also a type of physical activity that contributes to the development of aerobic and muscular fitness in other populations (Shephard, 1998). The official rowing races are carried out covering 2000-m on calm waters in different boats as classified by World Rowing Federation. Moreover, since 1981, races in specific ergometer have been regularly organized as a consequence of habitual use in training and evaluation of rower performance (Mäestu et al, 2005). In the mode of indoor rowing, 2000-m is the standard distance in official competitions.

The effort of rowing 2000-m races requires maintaining a continual and high intensity physical activity for 320- 420 seconds (Ingham et al, 2002), with rowers performing 210-230 strokes to 30-42 strokes per minute, producing 450 and 550 watts per stroke (Nybo et al, 2014; Steinacker, 1993). In both sexes, large body dimensions (Hagerman, 1984; Huang et al, 2007; Secher, 1983) and a low body fat percentage (Kerr et al., 2007) are anthropometric variables that correlate with rowing performance in 2000-m events. Furthermore, peak aerobic power (Nevill et al, 2011), production of anaerobic energy (de Campos Mello et al, 2009) and VO₂max (Cosgrove et al, 1999) are key physiological factors in achieving high performance in this sport modality. Rowing ergometer Concept 2 (Morrisville, Vermont, USA) is a mechanical simulation device (Smith & Hopkins, 2012; Van Holst, 2012) that offers a reliable measure of stroke power (Guével et al, 2006). It is normally used to monitor rowers' training and physiological evaluation. In this sense, time in 2000-m performance test on rowing ergometer is considered a standard test for fitness and performance assessment for high level rowers (Mikulić et al, 2009).

Hence, the aim of this study was to produce percentile curves and reference data for performance in 2000-m maximum test made on rowing ergometer Concept 2 for men and women aged 14-70 in light- and heavyweight divisions. These percentiles are of interest in evaluating indoor rowing and in defining reference values for the assessment of the specific physical condition of men and women rowers on-water. In addition, percentiles can be useful in predicting short, half and long-term specific performance for rowers.

MATERIALS AND METHODS

Sample

A cross-sectional study was carried out from a non-probabilistic sample (n=15420), obtained from an on-line ranking of indoor rowing made from results in official races since 2002. Different filters were applied to determine cases included in the sample. A first was applied to select results according to the 2000-m official distance race (n=174589). Secondly, data before September 2010 (n=121107), data non-official races (n=34179), ages outside 14-70 range (n=311), old data for the same individual (n=3536) and atypical values (n=36) were excluded. Finally, four study groups were made according to indoor rowing body-mass categories, heavyweight (> 75 kg) men rowers (n= 6337), lightweight (≤ 75 kg) men (n=3218), heavy-weight (> 61.5 kg) women (n= 4023) and lightweight (≤ 61.5 kg) women (n=1842).

Procedures

Data were obtained on-line from <http://log.concept2.com/ranking.asp>, website with official results of national and international indoor rowing races since 2002. In indoor rowing races model D Concept 2 ergometer (Morrisville, Vermont, USA) is used, since it is a device with a good reliability in measuring average power in 2000-m maximum test (Vogler et al, 2007). Rower chronological age was established as explanatory variable

(years) and time invested to cover 2000-m in rowing ergometer was the performance indicator and response variable (seconds) to design percentiles curves and calculate reference values. Time in 2000-m (s) is an indirect measure of average mechanical power output (w) and is based on the mathematical model provided by ergometer supplier: $\text{power} = 2,80 / \text{time in 2000-m} / 2000^3$. Four groups according to sex (men and women) and body-mass classification (light- and heavyweight) were considered. Percentiles range was established in accordance with the proposal included in the study for the development of children growth standards of the World Health Organization Multicentre Growth Reference Study Group (Borghi et al., 2006).

Statistical analysis

Atypical values were removed from the sample according to the conservative rule: $x < Q(25) - 3 \cdot IQR$ or $x > Q(75) + 3 \cdot IQR$. Kolmogórov-Smirnov were used to assess normality for the distributions. The U-Mann-Whitney test was used to evaluate differences between sex and weight in 2000-m performance and the corresponding effect sizes were calculated with r -Rosenthal value. This analysis was carried out with IBM SPSS Statistics software for Mac OS X, version 20.0 (SPSS, an IBM Company, Armon, NY). Generalized Additive Models for Location, Scale and Shape (GAMLSS) were applied (Rigby & Stasinopoulos, 2006) to draw the percentile curves and to estimate the reference values in each group. Data distributions for the response variable (seconds) were modelled using the Box-Cox Power Exponential distribution (BCPE) and the cubic splines technique was applied as smoothing method to explain the parameters of the BCPE distribution as a function of the explanatory variable (age). Worm plots (Buuren & Fredriks, 2001) were achieved for fit goodness assessment. The "gamlss" package of the R statistical software (R Core Team, 2016) was used to carry out this analysis (Stasinopoulos & Rigby, 2007).

RESULTS

Data about nationality of rowers are summarized in Table 1 and show presence in the sample of countries with top performance in international rowing races ($n=34$) with an outstanding percentage of USA rowers ($> 49.7\%$), especially in the heavyweight women group (59.6%).

Table 1. Sample distribution according to rower's nationality

Country	Men		Women	
	BM> 75 kg (n= 6337)	BM≤75 kg (n=3218)	BM> 61.5 kg (n=4023)	BM≤61.5 kg (n=1842)
Germany	8,80%	11,20%	5,50%	8,30%
Australia	2,50%	1,00%	2,80%	3,40%
Canada	3,90%	8,00%	7,00%	11%
Denmark	2,70%	2,00%	2,00%	1,40%
United of States	49,70%	56,70%	65,30%	59,60%
France	11,90%	7,60%	5,00%	5,40%
Ireland	3,80%	1,50%	3,00%	1,80%
United Kingdom	14,80%	9,90%	8,30%	7,30%
Others countries	1,9%	2,1%	1,1%	10,1%

Note: body-mass (BM). Heavyweight men rowers (body-mass >75 kg), lightweight men rowers (body-mass ≤75 kg), heavyweight women rowers (body-mass >61.5 kg), lightweight women rowers (body-mass ≤61.5 kg).

For the four study groups, the hypotheses of normal distribution ($p < 0.01$) were refuted for response variable (seconds). Likewise, asymmetry and kurtosis determined values of positive asymmetry (> 0.5) and leptokurtosis (> 0.5) in the four groups, with the exception of kurtosis (< 0.5) for the group of men in the lightweight division.

Data show trivial and significant statistical differences ($p < 0.01$) of performance (time) between heavyweight and lightweight rowers in both sexes (effect sizes $r = 0.16$ for men and $r = 0.23$ for women). These differences are medium-large between men and women ($p < 0.01$) for the same body-mass category (effect sizes $r = 0.69$ for heavyweight division and $r = 0.74$ for lightweight division).

Performance percentile curves (seconds to cover 2000-m) for men and women in two body-mass categories are presented in Figures 1-2 and also numerical values of percentiles are shown in Tables 2-5. Curves for P_2 , P_{10} , P_{25} , P_{50} , P_{75} , P_{90} and P_{98} percentiles and reference values for P_2 , P_5 , P_{10} , P_{15} , P_{25} , P_{50} , P_{75} , P_{85} , P_{90} , P_{95} and P_{98} percentiles are defined between 14 and 70 years old in the four study groups.

Percentile curves show a similar trend in all groups and plots are smoother and more regular in men than women. Two phases are identified for the evolution of performance with age. The first phase (from 14 years to 18-25 years according to group and percentile) corresponds to fast and exponential growth of performance. The second phase (from maximal performance age up to 70 years old) presents a continual and linear decline in 2000-m maximum test performance.

Meaningful differences in the plot of the curves are observed between more extreme percentiles (P_2 and P_{98}) especially for the 20-40 years old interval and in heavyweight women group. Tables 2-5 show the maximum performance age by group in each percentile.

Specifically, for percentile P_2 peak performance age is 23 years old for men (in both weight categories), 25 years old for heavyweight women and 24 years old for the lightweight women group. Worm plots showed that good fits of the model were obtained in every curve and reference values, although these were somewhat lower for poor performance percentiles ($> P_{95}$) in each group.

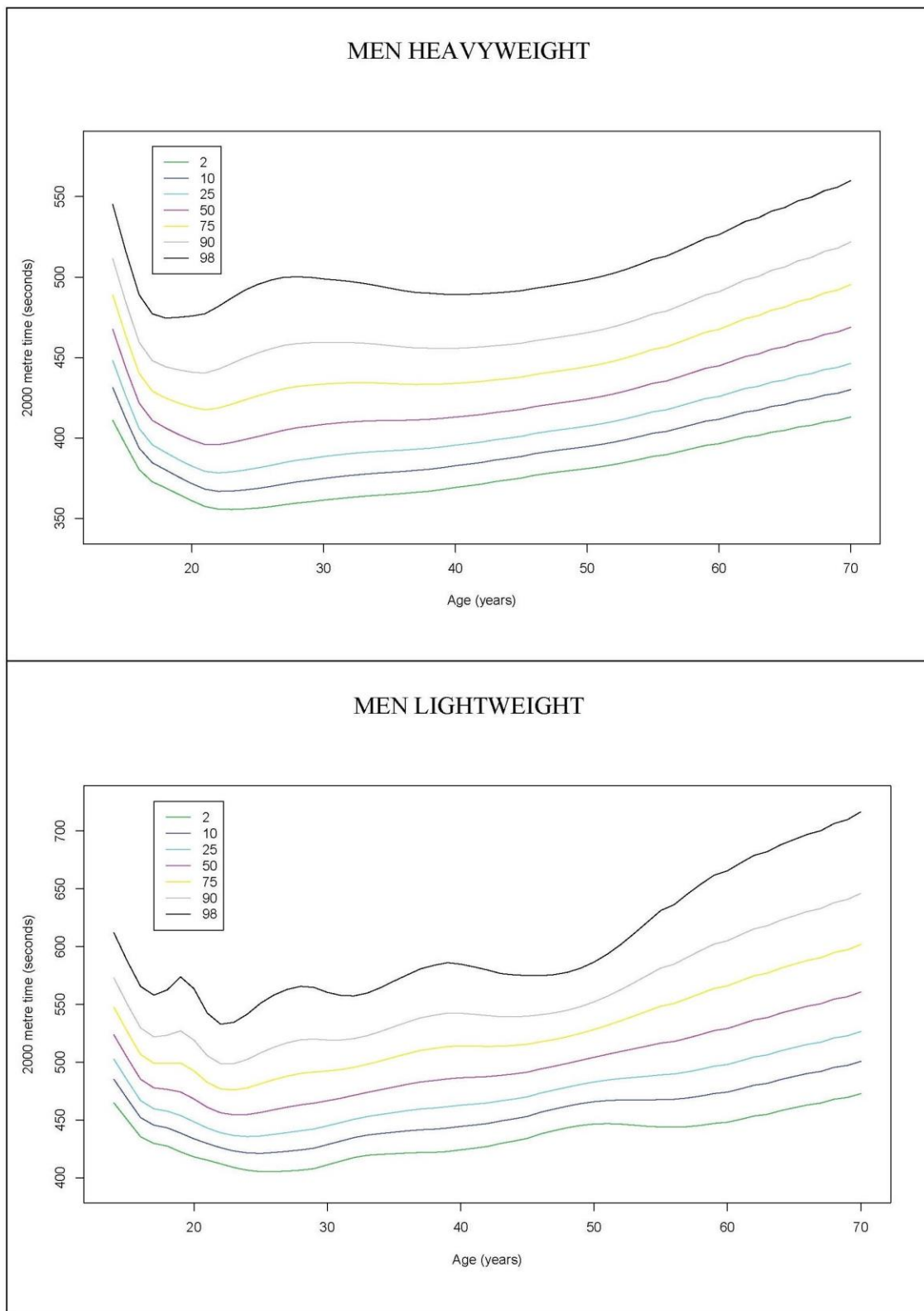


Figure 1. Percentile curves for 2000-m time (s) on rowing ergometer (age 14-70 years) for heavyweight men rowers (body-mass > 75 kg) and for lightweight men rowers (body-mass ≤ 75 kg).

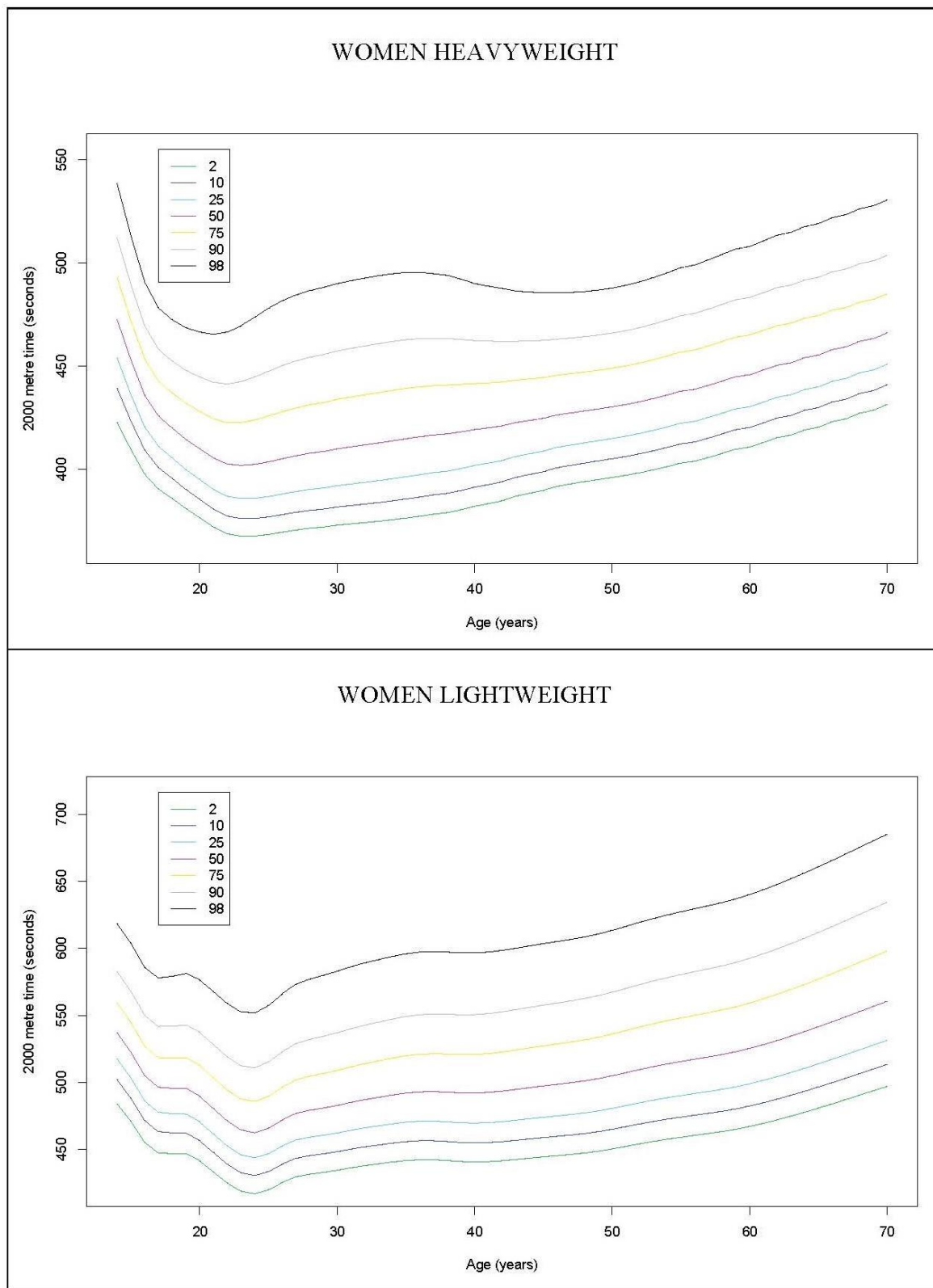


Figure 2. Percentile curves for 2000-m time (s) on rowing ergometer (age 14-70 years) for heavyweight women rowers (body-mass > 61.5 kg) and for lightweight women rowers (body-mass ≤ 61.5 kg).

Table 2. Reference values for 2000-m time (s) on rowing ergometer (age 14-70 years) for heavyweight men rowers (n= 6337)

age	P ₂	P ₅	P ₁₀	P ₁₅	P ₂₅	P ₅₀	P ₇₅	P ₈₅	P ₉₀	P ₉₅	P ₉₈
14	410,4	420,9	430,6	437,3	447,3	466,7	488,0	501,0	510,4	525,5	544,2
18	368,7	374,3	379,8	383,9	390,7	405,9	424,5	435,8	444,0	457,3	474,3
19	365,0	370,4	375,8	379,9	386,6	402,2	421,8	433,7	442,4	456,6	474,9
20	360,9	366,2	371,6	375,7	382,5	398,6	419,1	431,7	440,9	456,0	475,7
21	357,4	362,8	368,2	372,3	379,3	396,0	417,5	430,6	440,3	456,2	477,1
22	355,8	361,3	366,9	371,1	378,3	395,8	418,4	432,2	442,5	459,2	481,3
23	355,5	361,2	367,0	371,4	378,9	397,1	420,9	435,5	446,2	463,8	487,0
24	355,9	361,7	367,7	372,3	380,1	399,1	423,8	438,9	450,0	468,2	492,1
25	356,5	362,5	368,7	373,4	381,5	401,0	426,3	441,7	453,1	471,6	495,8
30	361,3	368,0	374,8	379,8	388,4	408,4	433,5	448,5	459,3	476,8	499,0
40	369,0	375,9	382,6	387,5	395,4	412,9	433,9	446,5	455,7	470,5	489,2
50	381,0	387,9	394,7	399,5	407,4	424,2	444,3	456,5	465,4	479,9	498,3
60	396,7	404,4	411,9	417,3	426,1	445,2	467,9	481,5	491,3	507,1	526,8
70	412,7	421,3	429,8	436,0	446,1	468,5	495,0	510,4	521,4	538,6	559,6

Note: heavyweight men rowers (body mass >75 kg).

Table 3. Reference values for 2000-m time (s) on rowing ergometer (age 14-70 years) for lightweight men rowers (n=3218)

age	P ₂	P ₅	P ₁₀	P ₁₅	P ₂₅	P ₅₀	P ₇₅	P ₈₅	P ₉₀	P ₉₅	P ₉₈
14	422,3	430,8	438,8	444,5	453,4	471,9	492,2	503,6	511,5	523,5	537,5
18	385,6	390,4	395,3	399,0	405,2	419,7	436,7	446,0	452,2	461,5	472,2
19	381,2	385,7	390,4	394,0	400,1	414,7	432,2	441,7	448,1	457,7	468,8
20	376,6	381,0	385,6	389,1	395,2	410,0	428,2	438,1	444,9	455,0	466,6
21	372,2	376,4	380,9	384,4	390,5	405,7	424,6	435,1	442,3	453,0	465,5
22	368,9	373,1	377,5	381,0	387,1	402,8	422,6	433,7	441,3	452,9	466,4
23	367,6	371,8	376,2	379,7	385,9	401,9	422,7	434,5	442,5	454,9	469,5
24	367,7	371,9	376,3	379,8	386,1	402,5	424,2	436,5	445,1	458,2	473,9
25	368,5	372,6	377,1	380,6	387,0	403,8	426,2	439,0	447,9	461,7	478,3
30	372,9	377,1	381,7	385,4	392,0	409,9	433,8	447,6	457,2	472,0	489,9
40	381,9	386,4	391,1	394,9	401,7	419,1	441,5	454,0	462,5	475,4	490,4
50	396,1	400,5	405,1	408,7	414,9	430,3	449,0	459,2	466,1	476,3	487,9
60	411,1	415,8	420,6	424,3	430,7	446,2	465,4	476,2	483,6	495,0	508,4
70	431,1	435,8	440,7	444,4	450,6	465,8	484,8	495,7	503,4	515,4	530,2

Note: lightweight men rowers (body mass ≤75 kg)

Table 4. Reference values for 2000-m time (s) on rowing ergometer (age 14-70 years) for heavyweight women rowers (n=4023).

age	P ₂	P ₅	P ₁₀	P ₁₅	P ₂₅	P ₅₀	P ₇₅	P ₈₅	P ₉₀	P ₉₅	P ₉₈
14	464,1	474,7	484,6	491,5	502,1	523,0	546,7	561,3	572,0	589,4	611,3
18	427,2	435,2	442,9	448,5	457,4	476,3	499,1	513,2	523,6	540,9	563,3
19	422,5	430,7	438,7	444,6	453,9	474,4	499,5	515,3	527,2	547,1	573,7
20	418,2	426,0	433,7	439,3	448,3	468,2	492,5	507,8	519,2	538,2	563,4
21	415,5	422,7	429,7	434,8	443,1	461,1	482,8	496,1	505,9	521,9	542,6
22	412,5	419,5	426,3	431,2	439,2	456,5	477,3	489,9	499,1	514,0	532,9
23	409,0	416,1	423,1	428,2	436,4	454,4	476,1	489,2	498,8	514,4	534,3
24	406,5	414,0	421,4	426,8	435,5	454,7	478,1	492,4	502,8	519,9	541,9
25	405,3	413,3	421,1	426,8	436,1	456,7	481,8	497,3	508,7	527,4	551,6
30	410,8	419,7	428,3	434,6	444,6	466,4	492,3	507,9	519,3	537,5	560,5
40	423,8	434,2	444,2	451,4	462,7	486,4	514,0	530,5	542,5	561,6	585,3
50	446,4	456,4	465,8	472,5	482,9	504,2	528,1	542,1	552,1	567,7	586,7
60	448,4	461,7	474,5	483,7	498,4	529,6	566,6	589,1	605,7	632,5	666,5
70	472,5	486,6	500,2	510,2	526,0	560,2	601,4	626,8	645,5	676,2	715,7

Note: heavyweight women rowers (body mass >61.5 kg)

Table 5. Reference values for 2000-m time (s) on rowing ergometer (age 14-70 years) for lightweight women rowers (n=1842)

age	P ₂	P ₅	P ₁₀	P ₁₅	P ₂₅	P ₅₀	P ₇₅	P ₈₅	P ₉₀	P ₉₅	P ₉₈
14	484,1	493,4	502,1	508,2	517,8	537,2	559,4	572,8	582,7	598,5	618,4
18	446,8	454,7	462,4	467,9	476,7	495,6	518,1	531,8	541,9	558,2	579,2
19	446,7	454,5	462,1	467,6	476,4	495,5	518,5	532,5	542,8	559,6	581,2
20	441,5	449,1	456,5	461,9	470,6	489,7	512,8	526,9	537,4	554,4	576,4
21	433,4	440,7	447,9	453,2	461,7	480,7	503,8	517,9	528,4	545,6	567,9
22	425,1	432,2	439,2	444,4	452,8	471,5	494,5	508,7	519,2	536,4	559,0
23	418,9	425,8	432,6	437,7	446,0	464,6	487,7	501,9	512,4	529,8	552,6
24	416,9	423,7	430,5	435,5	443,8	462,5	485,8	500,2	510,9	528,5	551,7
25	419,9	426,7	433,5	438,6	446,9	465,9	489,7	504,4	515,4	533,4	557,3
30	434,4	441,3	448,3	453,5	462,3	482,8	508,9	525,0	536,9	556,6	582,6
40	440,7	447,7	454,9	460,4	469,6	492,1	520,8	538,0	550,5	570,7	596,5
50	450,4	457,6	465,1	470,8	480,6	504,9	536,0	554,2	567,3	587,8	613,4
60	467,2	474,6	482,4	488,5	499,0	525,3	559,1	578,7	592,5	613,9	640,1
70	497,1	505,1	513,4	520,0	531,4	560,5	597,9	619,3	634,3	657,3	685,0

Note: lightweight women rowers (body mass ≤61.5 kg).

DISCUSSION

The results of this study provide the first curves and reference values for 2000-m performance time in indoor rowing races. Furthermore, this performance time test is also the most used standard test in evaluation of specific physical condition of on-water rowers (Akça, 2014). Percentile curves and reference values were calculated according to age (14 - 70 years old), sex (men or women) and official body-mass classification (light- and heavyweight). Sample size ($n=15420$) and rower nationality ($n=34$) determine a good representativeness for the population under study. Obtained references are relevant not only in indoor rowing but also in water competitive rowing.

Since 2000-m best time test on rowing ergometer is generally accepted as standard test to assess specific fitness in on-water rowers (Măestu et al., 2005). In this line one study made with men and women international rowers ($n=643$) founded for 12 of 23 events in the 2007 World Rowing Championship a moderate-to-strong correlation ($r=0.51-0.78$) between the performance on rowing ergometer and on-water rowing (Mikulić et al., 2009). This work provided data about 2000-m time performance for high-level rowers in events on-water, between 362 ± 4 s and 368 ± 12 s for open-category men, between 381 ± 11 s and 388 ± 8 s for lightweight men, between 411 ± 6 s and 420 ± 15 s for open-category women and between 433 ± 10 and 440 ± 13 for lightweight women. Other inquiries about performance rowing provide similar mean values (s) in this test, 364 ± 10 s for heavyweight men ($n=31$), 381 ± 7 s for lightweight men ($n = 23$) (Bourdin et al, 2004) and 421 ± 17 for heavyweight women (Nevillet al, 2011). Once positioning these data in percentile curves and values of the current study, the following percentiles are obtained: P_{10} percentile (for heavyweight men and women category), P_{25} percentile (for lightweight men category) and P_{15} percentile (for lightweight women category). These values define the cut-off point in 2000-m time performance on rowing ergometer for international rowers on-water with ages between 23-25 years old. So excellence percentiles ($> P_{95}$) (Seiler et al, 1998) on rowing ergometer are not necessary for high performance rowing on-water, this fact is probability due to rowing on-water requires different skills from those on rowing ergometer are needed.

Percentile curves and values show that peak performance age tends to be lower for poor performance percentiles ($> P_{90}$). This trend happens in every group with the exception of lightweight women, a group that maintains the same peak performance age (24 years) in all percentiles. On the other hand, the differences observed between extreme centile curves for the same age are probably due to the influence of the different training processes on performance of the participants in the event. In this sense, training may be considered a highlight interaction that changes peak and decline in 2000-m performance time on rowing ergometer depending on age.

The decrease in performance that occurs with increasing age deriving from the curves of the present study is in concordance with the decrease with age observed in the performance time in 2000 m on a rowing ergometer in other study ($n= 2487$ for men and $n=1615$ for women) about 2500-m best time on rowing ergometer between 24 – 94 years old (Seiler et al, 1998). This decline also agrees with the decrease in VO_{2max} with aging (Hawkins & Wiswell, 2003), physiological variable which has a strong correlation with rowing performance (Klusiewicz, & Faff, 2003; Lacour et al, 2009).

The main limitations of the study that must be acknowledged are its cross-sectional design, smaller sample size at ages 55 and over, especially in lightweight men and women categories, and a less accurate fit in the highest percentiles ($>P_{95}$) which correspond with the lowest performance. A likely interaction variable may be the training load developed by the rowers for the competitions. Due to the open participation of rowers in this type of races, training load is probably heterogeneous. Further research about performance on rowing

ergometer should be conducted to test the validity of percentiles in longitudinal studies and to use to determine optimal health levels in other populations.

Finally, these curves and reference values are of interest in assessing rowing performance and can be useful to delimit top-class rowers and to predict performance levels in oncoming ages.

CONCLUSIONS

This study presents the first percentile curves and reference data for evaluation in 2000-m performance time in rowing ergometer for both sexes and body-mass classifications (light- and heavyweight). Performance differences are more relevant between men and women than between rowers with different body-mass. These percentile curves and values are of interest in assessing the performance for indoor rowing and in measuring the specific physical condition for international rowers in 2000-m on-water regattas in the 14-70 years range. These percentiles can also be useful to evaluate training process quality and other performance changes which may result from disease, growing or ageing.

REFERENCES

- Akça, F. (2014). Prediction of Rowing Ergometer Performance from Functional Anaerobic Power, Strength and Anthropometric Components. *Journal of human kinetics*, 41(1), 133-142. <https://doi.org/10.2478/hukin-2014-0041>
- Borgh, E., de Onis, M., Garza, C., Van den Broeck, J., Frongillo, E. A., Grummer-Strawn, L., Van Buuren, S., Pan, H., Molinari, L., Martorell, R., Onyango, A. W. and Martines, J. C. (2006). Construction of the World Health Organization child growth standards: selection of methods for attained growth curves. *Statistics in medicine*, 25(2), 247-265. <https://doi.org/10.1002/sim.2227>
- Bourdin, M., Messonnier, L., Hager, J. P., & Lacour, J. R. (2004). Peak power output predicts rowing ergometer performance in elite male rowers. *International journal of sports medicine*, 25(5), 368-373. <https://doi.org/10.1055/s-2004-815844>
- Buuren, S. V. & Fredriks, M. (2001). Worm plot: a simple diagnostic device for modelling growth reference curves. *Statistics in medicine*, 20(8), 1259-1277. <https://doi.org/10.1002/sim.746>
- Cosgrove, M. J., Wilson, J., Watt, D. & Grant, S. F. (1999). The relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m ergometer test. *Journal of Sports Sciences*, 17(11), 845-852. <http://dx.doi.org/10.1080/026404199365407>
- Guével, Boyas, Nordez & Cornu (2006). Power responses of a rowing ergometer: mechanical sensors vs. Concept2® measurement system. *Int J Sports Med*, 27, 830-833. <http://dx.doi.org/10.1055/s-2006-923774>
- de Campos Mello, F., de Moraes Bertuzzi, R. C., Grangeiro, P. M. & Franchini, E. (2009). Energy systems contributions in 2,000 m race simulation: a comparison among rowing ergometers and water. *European journal of applied physiology*, 107(5), 615-619. <http://dx.doi.org/10.1007/s00421-009-1172-9>
- Hagerman, F. C. (1984). Applied physiology of rowing. *Sports Medicine*, 1(4), 303-326. <http://dx.doi.org/10.2165/00007256-198401040-00005>
- Hawkins, S. A. & Wiswell, R. A. (2003). Rate and mechanism of maximal oxygen consumption decline with aging. *Sports Medicine*, 33(12), 877-888. <http://dx.doi.org/10.2165/00007256-200333120-00002>
- Huang, C. J., Nesser, T. W., & Edwards, J. E. (2007). Strength and power determinants of rowing performance. *Journal of Exercise Physiology online*, 10(4).

- Ingham, S., Whyte, G., Jones, K. & Nevill, A. (2002). Determinants of 2,000 m rowing ergometer performance in elite rowers. *European journal of applied physiology*, 88(3), 243-246. <http://dx.doi.org/10.1007/s00421-002-0699-9>
- Kerr, D. A., Ross, W. D., Norton, K., Hume, P., Kagawa, M. & Ackland, T. R. (2007). Olympic lightweight and open-class rowers possess distinctive physical and proportionality characteristics. *Journal of Sports Sciences*, 25(1), 43-53. <http://dx.doi.org/10.1080/02640410600812179>
- Kleshnev, V. (2010). Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 224(1), 63-74. <https://doi.org/10.1243/17543371JSET40>
- Klusiewicz, A. & Faff, J. (2003). Indirect methods of estimating maximal oxygen uptake on the rowing ergometer. *Biology of Sport*, 20(3), 181-194.
- Lacour, J. R., Messonnier, L. & Bourdin, M. (2009). Physiological correlates of performance. Case study of a world-class rower. *European journal of applied physiology*, 106(3), 407-413. <https://doi.org/10.1007/s00421-009-1028-3>
- Mäestu, J., Jürimäe, J. & Jürimäe, T. (2005). Monitoring of performance and training in rowing. *Sports Medicine*, 35(7), 597-617. <https://doi.org/10.2165/00007256-200535070-00005>
- Mikulić, P., Smoljanović, T., Bojanić, I., Hannafin, J. A., & Matković, B. R. (2009). Relationship between 2000-m rowing ergometer performance times and World Rowing Championships rankings in elite-standard rowers. *Journal of sports sciences*, 27(9), 907-913. <https://doi.org/10.1080/02640410902911950>
- Nevill, A. M., Allen, S. V. & Ingham, S. A. (2011). Modelling the determinants of 2000 m rowing ergometer performance: a proportional, curvilinear allometric approach. *Scandinavian journal of medicine & science in sports*, 21(1), 73-78. <http://dx.doi.org/10.1111/j.1600-0838.2009.01025.x>
- Nybo, L., Schmidt, J. F., Fritzdorf, S. & Nordsborg, N. B. (2014). Physiological characteristics of an aging olympic athlete. *Medicine and science in sports and exercise*, 46(11), 2132-2138. <https://doi.org/10.1249/MSS.0000000000000331>
- R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>
- Rigby, R. A., & Stasinopoulos, D. M. (2006). Using the Box-Cox t distribution in GAMLSS to model skewness and kurtosis. *Statistical Modelling*, 6(3), 209-229. <http://doi.org/10.1191/1471082X06st122oa>
- Rubin, R. T. & Rahe, R. H. (2010). Effects of aging in Masters swimmers: 40-year review and suggestions for optimal health benefits. *Open access journal of sports medicine*, 1, 39. <http://doi.org/10.2147/OAJSM.S37718>
- Secher, N. H. (1983). The physiology of rowing. *Journal of Sports Sciences*, 1(1), 23-53. <http://doi.org/10.1080/02640418308729658>
- Seiler, K. S., Spirduso, W. W., & Martin, J. C. (1998). Gender differences in rowing performance and power with aging. *Medicine and science in sports and exercise*, 30(1), 121-127. <http://doi.org/10.1097/00005768-199801000-00017>
- Shephard, R. J. (1998). Science and medicine of rowing: a review. *Journal of Sports Sciences*, 16(7), 603-620. <http://doi.org/10.1080/026404198366416>
- Smith, T. B. & Hopkins, W. G. (2012). Measures of rowing performance. *Sports Medicine*, 42(4), 343-358. <http://doi.org/10.2165/11597230-000000000-00000>
- Soper, C. & Hume, P. A. (2004). Towards an ideal rowing technique for performance: The contributions from biomechanics. *Sports Medicine*, 34(12), 825-848. <http://doi.org/10.2165/00007256-200434120-00003>

- Stasinopoulos, D. M. & Rigby, R. A. (2007). Generalized additive models for location scale and shape (GAMLSS) in R. *Journal of Statistical Software*, 23(7), 1-46. <https://doi.org/10.18637/jss.v023.i07>
- Steinacker, J. M. (1993). Physiological aspects of training in rowing. *Evaluation*, 47(57), 60-62.
- Van Holst, M. (2012). On rowing. URL <http://home.hccnet.nl/m.holst/RoeiWeb.html>
- Vogler, A. J., Rice, A. J. & Withers, R. T. (2007). Physiological responses to exercise on different models of the concept II rowing ergometer. *International Journal of Sports Physiology and Performance*, 2(4), 360. <http://doi.org/10.1123/ijsp.2.4.360>



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